Experimental assessment of a fixed Oscillating Water Column coefficients as a damped harmonic oscillator

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Abstract—**During experimental test campaigns, it is important to estimate the quality of the numerical methods developed during the design stages of a wave energy converter. One of the most used methods for this purpose is to measure the diffraction and radiation forces experimentally. The present work addresses the experimental assessment of fixed Oscillating Water Column (OWC) coefficients as a damped harmonic oscillator. This work is a first step for the complete experimental assessment of the radiation force impulse response function of that OWC.The experimental setup consists of a simplified two-dimensionalgeometry of a fixed OWC in a 12.5 meter long wave flume. The top of the OWC is initially closed and the air chamber is depressurized with respect to the atmosphere, raising water column to certain decay height. Afterwards, the OWCtop coveris suddenly opened, column is dropped, and the motion of the oscillating water surface is recorded.Fitting the solution curve to a damped harmonic oscillation equation, its coefficients are calculated. The results are to be compared with a numerical model using SeaFEM software potential flow solver.**

Keywords—**Hydrodynamic coefficients, Oscillating Water Column, SeaFEM, Wave energy.**

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I. INTRODUCTION

SEEKING for new renewable energy resources is an important task in order to prevent a bigger damage of our environment and ensure a sustainable development [1-3]. Wave Energy Converters (WEC) have been under study for last 50 years as a solution to that objective [4, 5]. Several types of WEC systems and devices have been developed and most of them still are on that path. In this work we focus on one of the most relevant WEC: the Oscillating Water Column (OWC) [6-9]. This kind of technology can be separated in two groups: The floating and the fixed devices.

The "Ente Vasco de la Energía" (EVE, Basque Government), promoted a fixed OWC power plant in the village of Mutriku[10], Basque Country. The present work uses the geometry of this plant, scaled 1:64, and working in a laboratory wave flume in the School of Engineering of Bilbao (University of the Basque Country) will launch a set of experimental tests. The results obtained will be compared with numerical results from SeaFEM software using a potential flow solver.

The test consists in raising the water surface inside the chamber at certain height by making vacuum and suddenly opening to atmosphere so that raised water mass is dropped in a free decay. A computer controlled system capture the oscillations of the water surface.Water behavior can be fitted to a damped harmonic oscillation equation and its coefficients can be obtained. Different tide levels are experimented, so that certain range of real wave periods is covered.

II. DAMPED HARMONIC OSCILLATION ON FIXED OWC

A. Simple harmonic motion

The natural frequency of an OWC can be approximated considering the water column behaviour as of a rigid body of mass $m_1 + A_2 + A_\infty$ such that,

$$(m_1 + A_2 + A_\infty)\,\ddot{x} = -\rho g S_1 x, \tag{1}$$

where x is the OWC free surface displacement, m_1 is the mass of the vertical part of the OWC, A_2 is the mass of the entrance to the chamber, A_∞ is an approximation of the added mass, ρ is the water density and g is gravity acceleration, see Fig. 1.

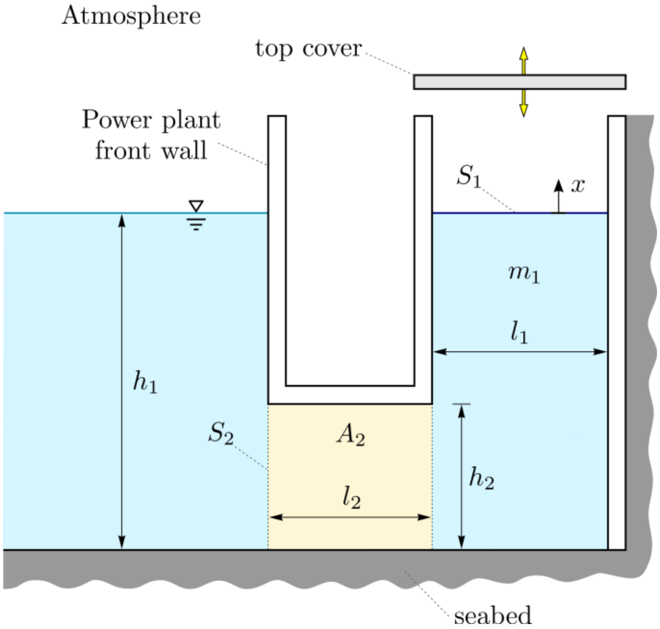

Fig. 1. Fixed Oscillating Water Column 2D view.

The natural frequency is computed as

$$\omega_0 = \sqrt{\frac{\rho g S_1}{m_1 + A_2}}, \tag{2}$$

where ω_0 is the natural frequency. Furthermore, since $m_1 = \rho h_1 S_1$ and $A_2 = \rho l_2 S_2$ we get

$$\omega_0 = \sqrt{\frac{g}{h_1 + l_2 S_2 / S_1}}. \tag{3}$$

Then, the period is simply

$$T_0 = \frac{2\pi}{\omega_0}. \tag{4}$$

The OWC geometry presented is this work is a 2D case of the Mutriku OWC power plant (Basque Country)[1]. A 1:64 scale factor has been used in all computations and experiments. Different tide levels (h_1, see Fig. 1), were used in order to find different resonance frequencies. Froude similarity condition scales time as $T_{0,p} = T_{0,m}\sqrt{\lambda}$. As an example case, in a 1:64 scaled test with a tide level of $h_1 = 0.3$m, the expected water column oscillating period inside the chamber model is $T_{0,m} = 1.26$s and so, in prototype scale would be $T_{0,p} = 10.07$ s. In Table I approximately calculated periods are shown for different tide levels at both scales, 1:64 and 1:1.

TABLE I
PERIOD CORRELATION BETWEEN 1:64 AND 1:1 FOR DIFFERENT TIDE LEVELS

Tide Level 1:64 (m)	Period 1:64 (s)	Period 1:1 (s)
0.200	1.08	8.7
0.234	1.15	9.2
0.300	1.26	10.07
0.400	1.41	11.28
0.500	1.55	12.37
0.600	1.67	13.37

B. *Damped harmonic motion*

The general equation for a linear damped harmonic oscillation is of the type

$$(m_1 + A_2 + A_\infty)\,\ddot{x} + B\dot{x} + \rho g S_1 x = 0. \tag{5}$$

When the damped oscillator is underdamped, the solution equation is that of an exponentially decaying sinusoid

$$x = e^{-\gamma t} x_0 \cos(\omega t - \theta), \tag{6}$$

where x_0 is the amplitude of the displacement of the OWC free surface from its equilibrium position. The damping coefficient is

$$\gamma = \frac{B}{2(m_1 + A_2 + A_\infty)}, \tag{7}$$

and the angular frequency for the damped harmonic motion [11] is given by (see Fig. 2).

$$\omega = \sqrt{\omega_0^2 - \gamma^2}, \tag{8}$$

and θ is the phase of the system response.

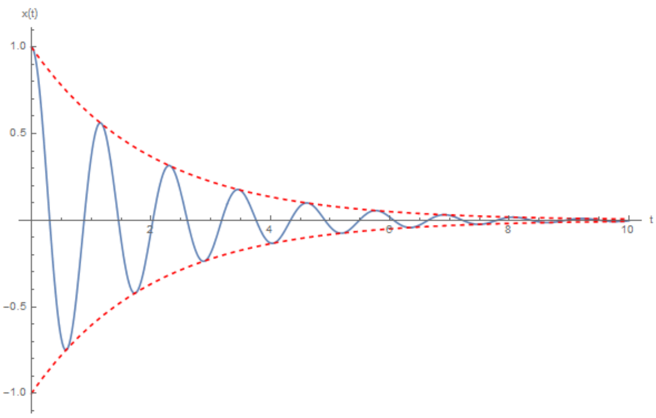

Fig. 2. Underdamped solution equation is an exponentially decaying sinusoid

III. SEAFEM

SeaFEM is a suite of tools for the computational analysis of the effect of waves, wind and currents on naval and offshore structures, as well as for manoeuvring studies. SeaFEM includes a 3D multi-body radiation and diffraction, potential flow solver in the time domain, using the finite element method on unstructured meshes. SeaFEM solves first and second order diffraction-radiation equations with real sea spectra, enabling direct time-domain analyses of the dynamic response of structures and oscillating water columns. [12-15]

IV. EXPERIMENTS

Mutriku fixed OWC power plant[10]two-dimensional side dimensions have been scaled 1:64 (see TableII)and a specific model has been manufactured (see Fig.3 and Fig.4). The model has been installed in the 12.5-meter long wave flume (see Fig. 4) located in the Engineering School of Bilbao (University of the Basque Country, UPV/EHU). This new wave flume is an evolution of a previous smaller one [16]. The wave flume is 600 mm width and 700 mm high. For the test, we do not need to use the wave maker; we just need to make a specific vacuum inside the OWC chamber so internal water levelrises until a defined height (water decay) respect to the level outside the OWC chamber (sea level or tide). Then, OWC chamber top cover is suddenly opened and water inside chamber is dropped down while free surface height is monitored by sensors. Solution is a damped harmonic oscillation of the water column.

TABLE II
DIMENSIONS FOR 1:1 MUTRIKU WAVE ENERGY POWER PLANT AND 1:64 SCALED MODEL ACCORDING TO FIGURE 1.

	h_1	l_1 (m)	h_2 (m)	l_2 (m)
Model (1:64)	tide	0.048	0.044	0.104
Prototype (1:1)	tide	3.10	2.80	6.65

Fig.3.Wave flume located at the Engineering School of Bilbao, University of the Basque Country.

C. Testing model (1:64 scale)

An *ad hoc* model has been manufactured according to dimensions presented on the 1:64 scaled model dimensions ofTable II. All used parts are specifically machined PVC plastic sheets assembled one to each other. In one of the sides, transparent PMMA has been used in order to see water surface level or any other macroscopic phenomena that occur inside the OWC chamber. Chamber internal height is 1 meter. Even if planned highest decay will only have a 650 mm water surface height, higher decays are available for future research. Top cover opening system has a vertical movement driven by a 50 mmstroke pneumatic cylinder.

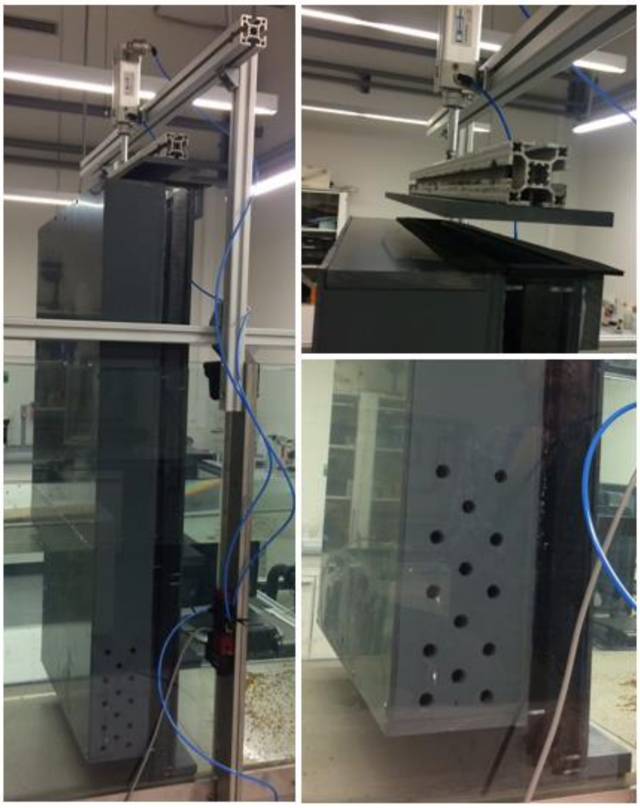

Fig.4. Manufactured model for experimental tests. Find on the left a general view. On the right top, cover opening system detail and on the right bottom detail of the OWC.

A pressure gauge and two ultrasonic sensorsare monitored by a computer. Whole testing process is controlled as well. The pressure gauge controls air pressure over water free surface inside OWC chamber and ultrasonic sensors read the water free surface height. First ultrasonic sensor is located at 800 mm from wave flume seabed and second sensor at 620 mm. A vacuum pump is connectedthrough pneumatic fittings to the chamber in order to reduce the air chamber pressure and raise the OWC free surface level.

1) *Ultrasonic sensors*

For the measurement of the water level on tests, two ultrasonic sensors are mounted (see Fig. 5). Both are the same model: PEPPERL+FUCHS UC500-L2-I-V15. Sensing range is between 30 and 500 mm.

2) *Pneumatic cylinder and valve*

The pneumatic cylinder makes the required force to open the top cover of the OWC chamber. It is a double action 32 mm diameter and 50 mm stroke pneumatic cylinder controlled by a 3/2 NC electromagnetic valve. The valve is operated from the computer.

D. Testing campaign

Table III is a summary of different tests carried out on the described facility. Each experiment has been repeated three times: a total of 54 tests have been done.

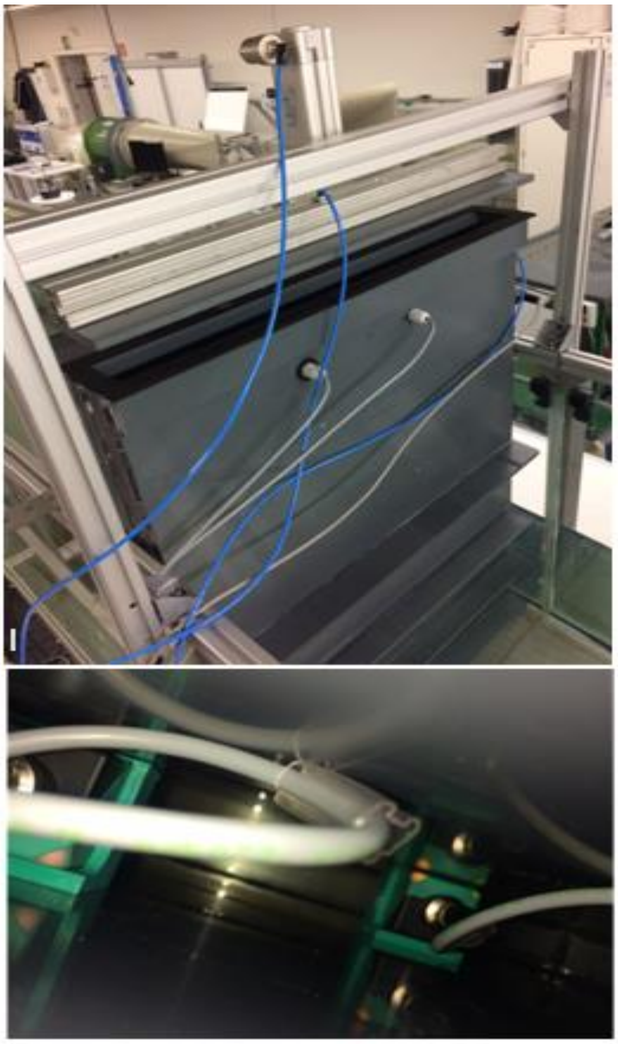

TABLE III
TEST CAMPAIGN SUMMARY

Tide Level 1:64 (mm)	Decay Level 1 (mm)	Decay Level 2 (mm)	Decay Level 3 (mm)
200	210	225	250
234	244	259	284
300	310	325	350
400	410	425	450
500	510	525	550
600	610	625	650

Fig.5.Two sensors are located inside the OWC chamber.

E. *Experiment description*

All data captured by sensors, pneumatic system control (valves and cylinder) and solution data recording is controlled by a computer (see GUI screenshot in Fig. 6). Experiment steps are programmed in LabVIEW[17, 18] giving the next sequence:

1. Required tide level is set on the whole wave flume.
2. Top cylinder pushes down the top cover and the chamber is completely closed.
3. Vacuum pump is switched on and chamber water level starts to rise.
4. Vacuum pump control valve is tuned in order to reach a required chamber water level.
5. Height sensors detect when required decay level is stable: reach 1000 sensor reading data with no more than 0.7 mm dispersion. Then, the pneumatic cylinder opens the chamber top cover.
6. Pressure sensor records data inside chamber along whole test.
7. Ultrasonic sensors record water level inside chamber with its corresponding time.

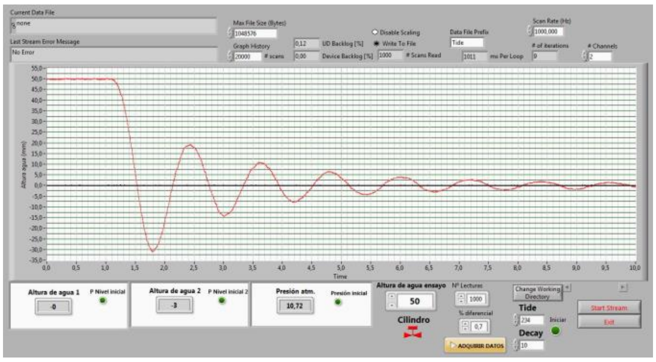

Fig. 6. Experiment control GUI screenshot.

F. *Data treatment*

As a result of the test, water level solution versus time is recorded and plotted. This data is treated so that fits a damped harmonic oscillation movement, as in (5), and A_∞ and$B$coefficients are obtained.

V. RESULTS

In this section, we present the obtained data for the test campaign presented in Table III.

G. *SeaFEM results*

First, results of SeaFEM simulations are presented in Fig.7.First order diffraction radiation potential flow solver has been used with geometry scaled to 1:64. The graph shows how periods and damping changes with the tide level. The period increases with the tide level while the damping decreases. As potential flow solver is used, no difference would appear in a normalized graph when different decay heights are done.

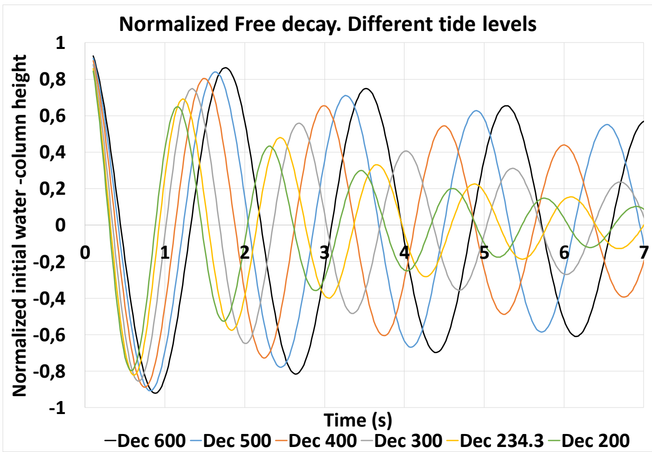

Fig.7. SeaFEM potential flow results. All tested tides are included.

H. *Experiments*

Water surface level behaviour inside OWC chamber data has been recorded using ultrasonic sensors and controlled by computer as explained in section IV. Experimental results are presented in Fig. 8, as a comparison with SeaFEM potential flow solver results, Fig. 7. In this graph, a 50 mm decay has been used for all tested tide levels.

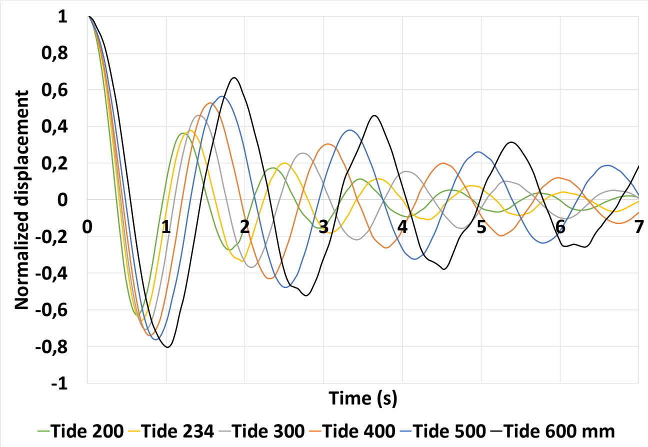

Fig.8. Experimental normalized 50 mm free decay. Different tidelevels are used.

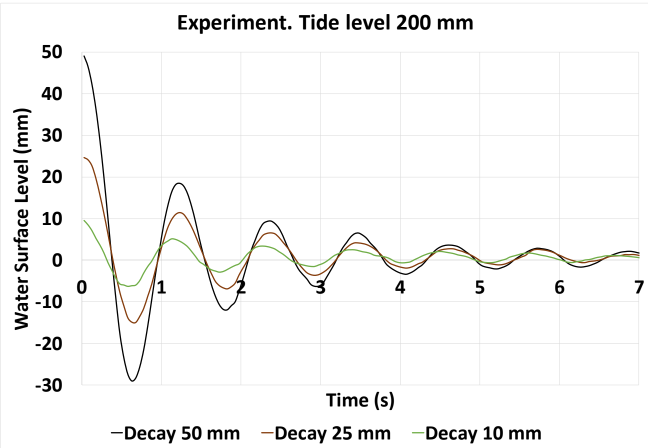

Fig.9. OWC free surface level behavior experimental result when using 200 mm sea level. Decays: 50 mm, 25 mm and 10 mm.

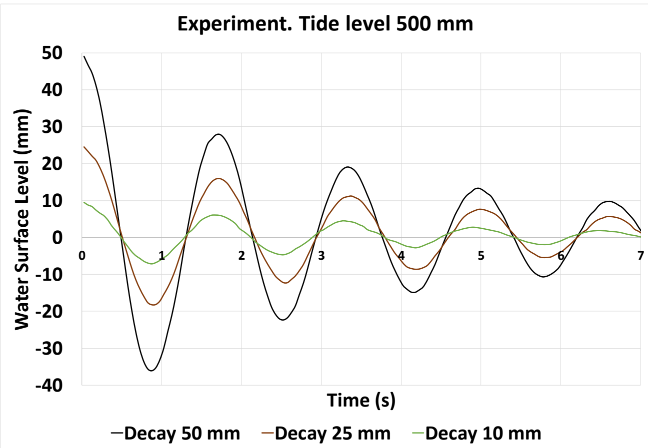

Fig. 10. OWC free surface level behavior experimental result when using 500 mm sea level. Decays: 50 mm, 25 mm and 10 mm.

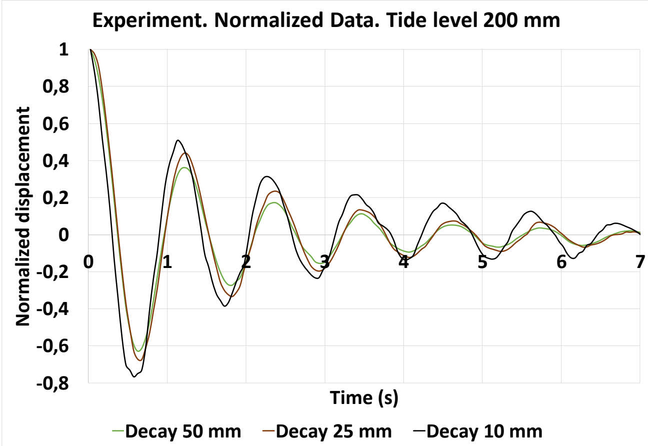

Fig. 11.Normalized data. OWC free surface level behavior experimental result when using 200mm sea level. Decays: 50 mm, 25 mm and 10 mm.

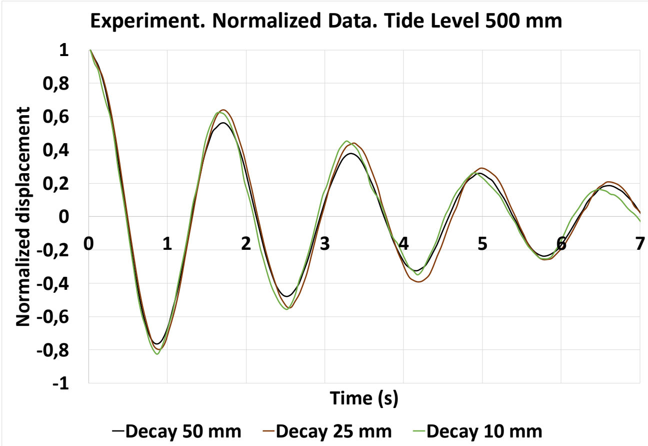

Fig. 12.Normalized data. OWC free surface level behavior experimental result when using 500 mm sea level. Decays: 50 mm, 25 mm and 10 mm.

In Fig. 9 and Fig. 10, OWC chamber level evolution is presented for two different tide levels (200 mm and 500 mm) among all tested cases. Each tide level has been tested with three decays: 50 mm, 25 mm and 10 mm. In Fig. 11 and Fig. 12 same two test cases are presented but with normalized data so that a more clear comparison can be done.

I. *Result comparison*

As explained in section II, the theoretical behaviour of the water surface follows an underdamped harmonic oscillation curve. In this work, all experimental data have been fitted to a curve that follows (5). Fitting has been realized using in-house developed software including non-linear least squares procedure following Levenberg-Marquardt algorithm as implemented in MINPACK [19, 20].In that fitting, angular frequency ω and damping coefficient $\gamma$are obtained. Using them, and following equations in section II, equation (5) coefficients $(m_1 + A_2 + A_\infty)$ and B are calculated.

$$m_1 + A_2 + A_\infty = \frac{k}{\omega^2 + \gamma^2}, \qquad (9)$$

$$A_\infty = \frac{k}{\omega^2 + \gamma^2} - (m_1 + A_2), \qquad (10)$$

$$B = 2(m_1 + A_2 + A_\infty)\gamma, \qquad (11)$$

with $k = \rho g S_1$.

Results of these two coefficients, A_∞ and B, are shown in Fig. 13 and Fig. 14. A_∞ gives a good fitting for all the presented cases. The coefficient B is more sensitive to different decays.

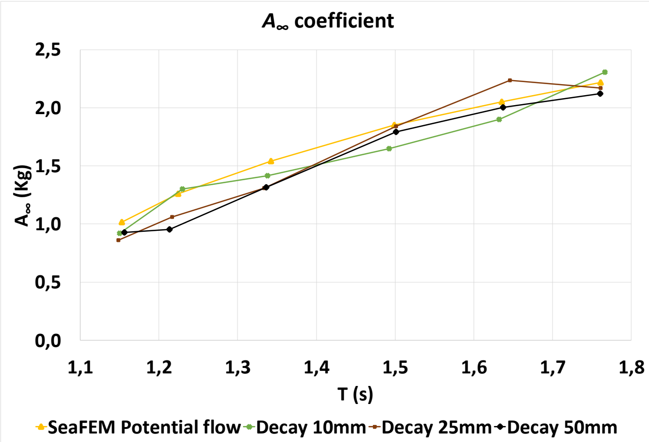

Fig. 13. A_∞ Coefficient for Damped Harmonic Oscillation equation on different decays.

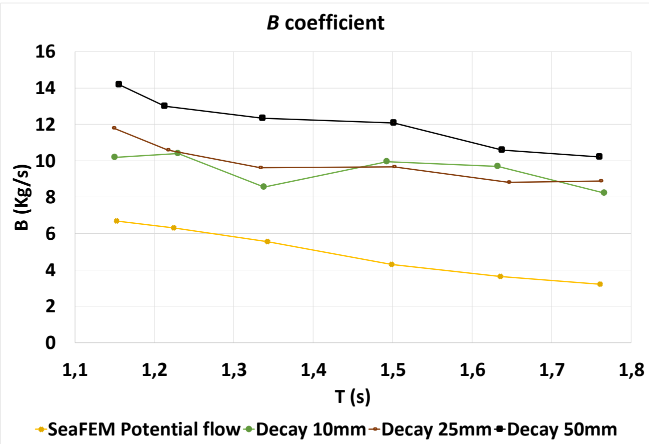

Fig. 14. B coefficient for Damped Harmonic Oscillation equation on different decays.

VI. Conclusion and Future Work

Results obtained from this work has shown that free decay test of water on OWC fixed chamber is a reasonable tool to understand the hydrodynamics of the system. Interesting lessons have been learned about experimental testing activity, especially when low decay test where achieved (10 mm). It is clear that the lowest decay we have, the closest to a potential flow behaviour will be, but testing conditions become much more sensitive.

The presented work is in the frame and scope of a more aspiring work where hydrodynamic coefficients and the radiation force impulse response function will be computed through a system identification procedure[13, 14, 21]. The results are to be compared with a numerical model based on the hydrodynamic coefficients calculated with the boundary element method compute code WAMIT.[13, 22]

Here, for the presented work, the RAO for a 234mm tide level has been computed using SeaFEM (see Fig. 15). Future work will include a comparison with WAMIT results and a non-linear approximation to include a quadratic damping.

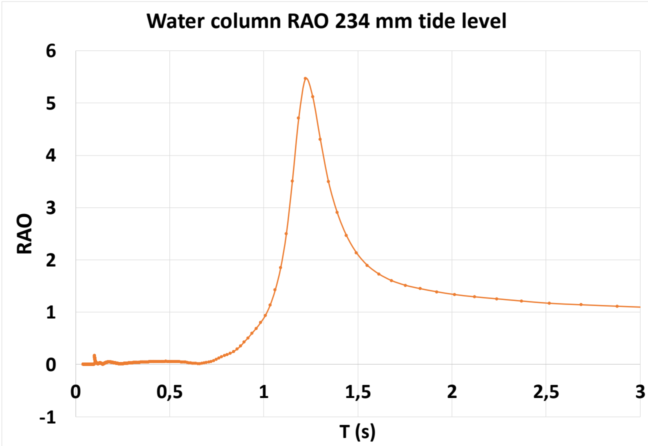

Fig. 15. RAO for 234 mm tide level.

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